




Electron–Nucleus Scattering in the NEUT Event Generator [†]

Stephen Dolan ^{1,*} , Jordan McElwee ^{2,*}, Sara Bolognesi ³, Yoshinari Hayato ⁴, Kevin McFarland ⁵ ,
Guillermo Megias ⁶ , Kajetan Niewczas ^{7,8}, Luke Pickering ⁹, Jan Sobczyk ⁷, Lee Thompson ² and Clarence Wret ⁵

¹ CERN European Organization for Nuclear Research, 1211 Genève, Switzerland

² Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

³ IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

⁴ Institute for Cosmic Ray Research, Kamioka Observatory, University of Tokyo, Kamioka 506-1205, Japan

⁵ Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

⁶ Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, 41080 Sevilla, Spain

⁷ Faculty of Physics and Astronomy, Wrocław University, 50-204 Wrocław, Poland

⁸ Department of Physics and Astronomy, Ghent University, 9000 Gent, Belgium

⁹ Department of Physics, Royal Holloway University of London, Egham TW20 0EX, UK

* Correspondence: stephen.joseph.dolan@cern.ch (S.D.); mcelwee@lp2ib.in2p3.fr (J.M.)

[†] Presented at the 23rd International Workshop on Neutrinos from Accelerators, Salt Lake City, UT, USA, 30–31 July 2022.

Abstract: The NEUT event generator is a widely used tool to simulate neutrino interactions for energies between 10 s of MeV and a few TeV. NEUT plays a crucial role in neutrino oscillation analyses for the T2K and Hyper-K experiments, providing the primary simulation of neutrino interactions, whose final-state products are measured to infer the oscillation parameters. NEUT is also capable of simulating nucleon decay and hadron scattering. These proceedings present an expansion of NEUT to simulate electron scattering before showing comparisons to experimental measurements and using discrepancies to derive an empirical correction to NEUT's treatment of nuclear removal energy.

Keywords: neutrino physics; lepton–nucleus interactions; event generators



Citation: Dolan, S.; McElwee, J.; Bolognesi, S.; Hayato, Y.; McFarland, K.; Megias, G.D.; Niewczas, K.; Pickering, L.; Sobczyk, S.; Thompson, L.; et al. Electron–Nucleus Scattering in the NEUT Event Generator. *Phys. Sci. Forum* **2023**, *8*, 5. <https://doi.org/10.3390/psf2023008005>

Academic Editor: Yue Zhao

Published: 28 June 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Robust predictions of neutrino interaction cross-sections, alongside their reliable uncertainties, are a critical ingredient in neutrino oscillation measurements at GeV-scale energies [1]. The currently operating T2K [2] and Super-Kamiokande [3] experiments, as well as the future Hyper-K [4] experiment, use the NEUT event generator to provide such predictions. A comprehensive overview of NEUT can be found in Ref. [5]. NEUT is able to simulate neutrino interactions with nuclei from the threshold of quasi-elastic scattering ($\sim 1\text{--}50$ MeV) up to TeV energy scales using a variety of theory-driven interaction models that can be chosen and configured by the user. Hadronic final-state interactions within the nuclear medium are modeled using an intranuclear cascade, which is tuned thanks to NEUT's ability to predict hadron-scattering measurements [6]. NEUT has a rich history, having been developed in the 1980s for atmospheric neutrino and nucleon decay studies and being used for Super-Kamiokande's Nobel-prize-winning analysis of neutrino oscillations [7]. NEUT continues to be developed primarily by the collaborators of experiments that use it.

In these proceedings, the first steps towards expanding NEUT's repertoire of scattering simulations to include electron–nucleus interactions is presented based on [8]. The comparison to electron-scattering measurements is a valuable tool to validate any neutrino interaction model. The form factors describing the vector component of neutrino interactions can be directly inferred from electron-scattering experiments, and the nuclear target in the weak and electromagnetic interaction is identical. Electron-scattering experiments

are also typically of much higher precision than their neutrino scattering counterparts, being able to produce mono-energetic beams with interaction cross-sections typically more than eight orders of magnitude larger (for the GeV-scale energies relevant to neutrino oscillation experiments). It is therefore unsurprising that recent years have seen a plethora of analyses of electron-scattering data tailored towards constraining poorly understood neutrino interaction physics [9–11].

2. Electron Scattering in NEUT

Weak neutral-current (NC), quasi-elastic (QE) neutrino–nucleus interactions are used as a basis to construct electromagnetic (EM) QE pseudo-electron scattering predictions within NEUT. This is carried out to remove any possible issues with the pure isovector contributions of charged-current (CC) QE interactions. However, using NC interactions as a framework assumes a neutral lepton in both the initial and final state. Neither of these are subject to the effects of the Coulomb potential that an electron would experience in a scattering interaction, and so a shift in final-state lepton energy is made to correct for this. In this analysis, we use 3.6 MeV for carbon and 4.1 MeV for oxygen [12,13].

In addition to the Coulomb correction, it is also necessary to change form factors used for NCQE scattering to replace the weak couplings with the EM couplings. These alterations are two-fold: the first is to set the axial form factors, F_A and F_P , to zero (Ref. [14] details how these enter the NCQE cross-section), and second is to change the electric and magnetic form factors to the simpler form required by the EM interactions. Finally, the weak coupling constant is replaced by its EM counterpart.

NEUT offers several nuclear models to predict the lepton scattering on a nuclear target. This analysis uses the Benhar spectral function model, which is based on the work presented in Refs. [5,15], and is used as the primary input model for T2K’s neutrino oscillation analyses. This approach relies on the plane wave impulse approximation (PWIA) to factorize the QE cross-section calculation into an expression containing a single-nucleon factor alongside a “spectral function” (SF). The single nucleon factor is altered from the usual neutrino scattering case using the prescription presented above, whilst the SF component remains unchanged. The SF is a two-dimensional distribution describing the probability of finding a nucleon with some particular momentum and removal energy, E_{rmv} , which corresponds to the energy required to remove the nucleon from the nuclear potential.

Whilst the SF model has been relatively successful in describing electron and neutrino scattering measurements, the use of a factorized PWIA calculation means that at low momentum transfer (q_3 less than ~ 300 – 400 MeV [16]), the model predictions are expected to be missing important components. For example, the use of PWIA implies that the nucleon removal energy “seen” by the incoming lepton is independent of the four-momentum of the impinging particle. More sophisticated models that consider effects beyond PWIA predict a relationship: the distortion of the outgoing nucleon wave function by the nuclear potential in a relativistic mean field (RMF) model finds a linear correlation between the momentum transfer and a shift from the PWIA expected peak of the QE interaction as a function of energy transfer, q_0 [17,18]. Such shifts in the QE peak are characteristic of a shifted removal energy [13]. Theory-driven corrections to the SF model have been suggested to account for this [19] but are not included in this study.

As detailed in Ref. [19], a mismodeling of shifts in the QE peak position can cause important biases in neutrino experiments’ ability to reconstruct neutrino energy, which causes biases in the measurements of neutrino oscillations. It is therefore imperative that the potential mismodeling of such shifts is scrutinized using both theory and experiments. Neutrino experiments have attempted to constrain this [20,21], but the broad incoming neutrino energy spectrum makes such analyses very challenging. Electron-scattering measurements are much better suited for this and are routinely used to study deviations in the QE peak position from expectations (see, e.g., [13,19]).

3. Comparison to Inclusive Electron-Scattering Data

Inclusive electron cross-section measurements on carbon [22] as a function of the incident beam energy, outgoing lepton angle, and the measured energy transfer are compared to NEUT EMQE predictions in Figure 1. A complete description of the data throughout the energy transfer range would require the prediction of inelastic interaction channels, which is beyond the scope of this work. However, in the region of the QE peak, a qualitative comparison between NEUT and the measurements can be made. Within this region, the NEUT prediction is shifted with respect to the data. The size of the shift is derived by fitting a fifth-order polynomial to determine the peak position of the prediction and the data, which is shown as smooth lines in Figure 1. Measurements with expected large inelastic contributions overlapping with QE peak regions are not used in this analysis, thereby limiting the range of momentum transfers considered.

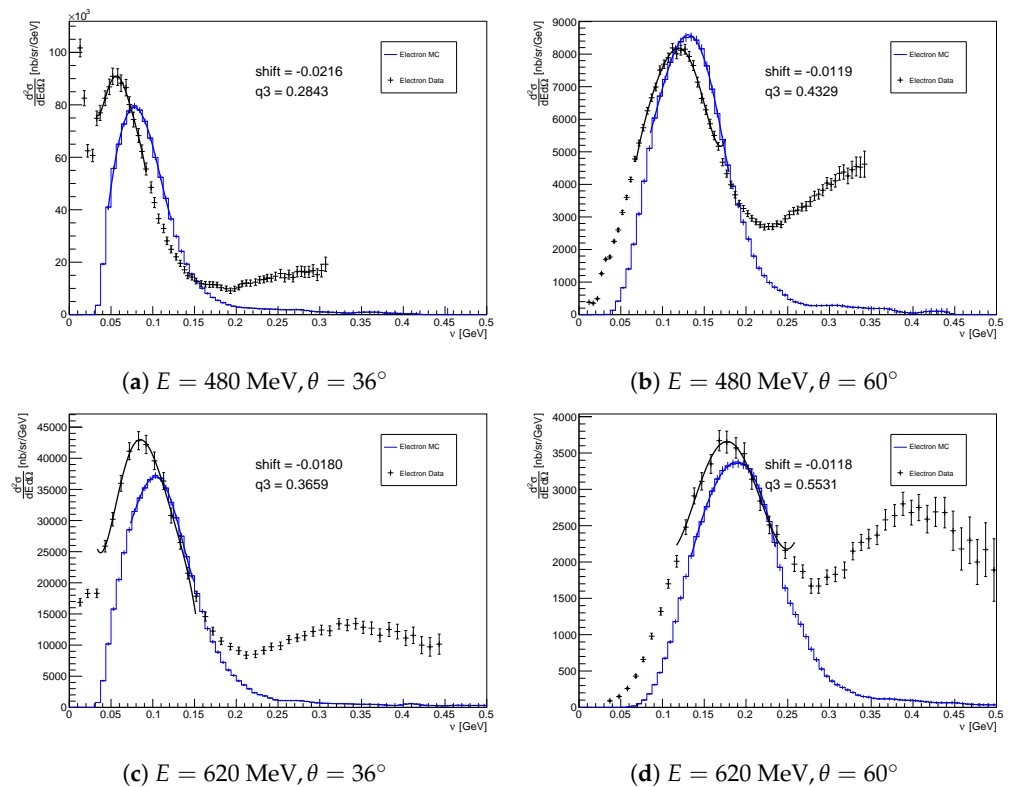


Figure 1. Inclusive electron cross-section measurements [22] (data points) compared to quasi-elastic electron-scattering generation in NEUT (blue histogram) as a function of energy transfer. The comparison is made for a number of different scattering angles and beam energies. The peaks are fitted with a fifth-order polynomial to extract the position (the smooth lines), and the difference between the peak positions is shown on each plot (“shift”, in GeV). The q_3 calculated at the peak position of the cross-section measurement (“ q_3 ”, in GeV/c).

4. Determining a Momentum-Transfer-Dependent Correction

As discussed in Section 2, given the limitations of NEUT’s PWIA-based nuclear model, the shift with respect to the QE peak is not surprising, and an evolution as a function of the momentum transfer is expected. To evaluate this, the derived shift is plotted against the momentum transfer (taken at the measured peak) in the left panel of Figure 2. A linear fit, which is also shown in the figure, is qualitatively reasonable to describe the evolution of the shift. The gradient was found to be 0.056, which corresponds to the same evolution as predicted from the aforementioned RMF model [17,18].

A naive correction for the breaking of factorization can be built by shifting the removal energy of NEUT’s SF model as a function of the momentum transfer according to the linear fit. As this is an empirical correction to the model, it is able to shift some small fraction of

the SF removal energy distribution to be negative at large values of momentum transfer. To alleviate this issue, negative removal energies are truncated at zero. It was verified that the truncation has a small impact on the corrected NEUT predictions.

Applying the correction during event generation has the expected result of more accurately predicting the electron-scattering data. This is demonstrated in the right panel of Figure 2, which shows that the evolution derived from the corrected distribution is close to zero for all values of momentum transfer.

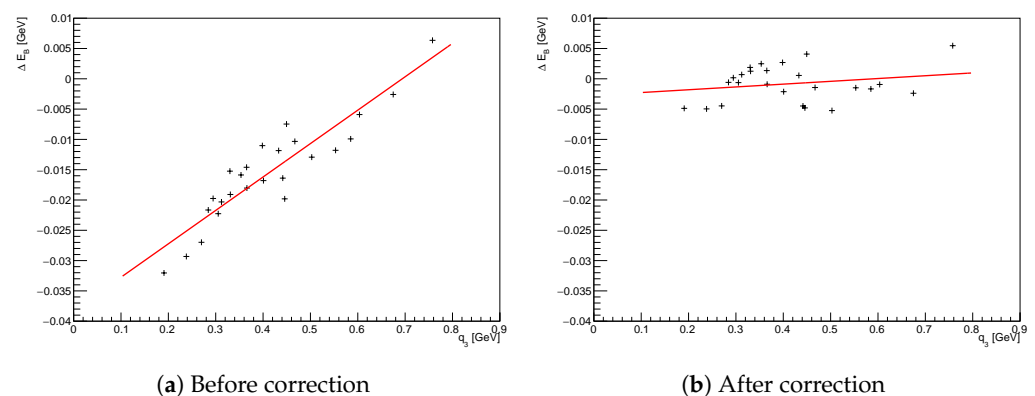


Figure 2. The shifts derived from Figure 1 are shown as a function of momentum transfer to reveal an approximately linear relationship, as described by the fitted line (a). The derived shift is interpreted as an E_{rmv} correction and applied within NEUT, and the shifts are re-derived for the corrected model, showing there is no need for further corrections (b).

5. Relevance for Neutrino Scattering

It is interesting to consider the effect of the correction on NEUT's simulation of neutrino interactions. To study this, the impact of the correction on neutrino energy reconstruction metrics and CCQE cross-sections on a carbon target using the T2K ν_μ flux are shown in Figure 3. The correction causes a shift in and broadening of the cross-section as a function of energy transfer and reconstructed neutrino energy. This is expected from Figure 2 since, for most regions of momentum transfer, the correction tends to shift the removal energy to smaller values, thereby permitting interactions with lower energy transfer and biasing of the neutrino energy reconstruction. The impact on the neutrino energy reconstruction bias is considerable and, if taken as an unconstrained uncertainty, may be a dominant effect. This applies equally whether neutrino energy is reconstructed using T2K's approach, based on only the outgoing lepton kinematics [20], or with the NOvA's approach, using total observed energy deposits [23]. For this reason, T2K's latest oscillation analysis [24] uses a model which fully brackets this uncertainty [25].

Whilst the impact of the correction on neutrino energy reconstruction spread and bias appears to be large, the extrapolation of the correction from electron-scattering data is not guaranteed to be reliable. The qualitative nature of the analysis and the need to truncate the correction to avoid non-physical removal energies, discussed in Section 4, is important to keep in mind. Furthermore, the q_3 range covered by the considered electron-scattering measurements is situated below the expected peak q_3 for T2K (0.5 GeV, extending up to about 1 GeV), meaning much of the correction is applied to NEUT events in a q_3 range, which is relatively poorly constrained. Moreover, whilst the nuclear target is unchanged, the aspects of the nuclear response probed by EM and weak interactions are not guaranteed to be the same.

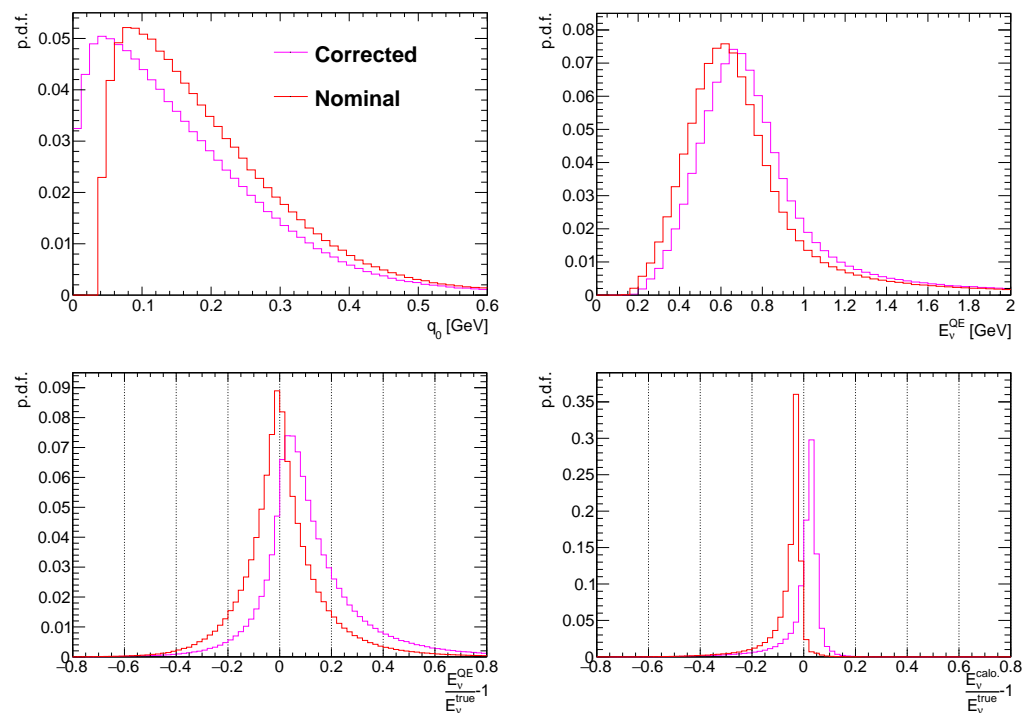


Figure 3. The NEUT simulation for CCQE interactions applying (magenta) and not applying (red) the derived q_3 -dependent removal energy correction on a carbon target using the T2K ν_μ flux. The upper plots show the cross-section shape as a function of the energy transfer (**left**) and reconstructed neutrino energy (**right**), using the neutrino energy estimator from T2K (using lepton kinematics only [20]). The lower plots show the bias and spread of the neutrino energy estimators used by T2K (**left**) and NOvA (**right**, using total energy deposits estimated using E_{avail} from Ref. [26]).

6. Conclusions

The NEUT event generator has been updated to simulate EMQE interactions. Predictions from the updated generator have been compared to inclusive, QE-dominated, electron-scattering measurements to derive an empirical momentum-transfer-dependent correction to the nuclear removal energy in NEUT's SF nuclear model. The correction has an important impact on neutrino energy reconstruction metrics and is considerably relevant for current and future neutrino oscillation analyses. A more sophisticated analysis involving the simulation of inelastic scattering channels would permit a more robust correction to be derived. A detailed comparison of electron and neutrino cross-section predictions from the corrected NEUT to more sophisticated nuclear models, which go beyond the PWIA prescription, would better inform its applicability to neutrino–nucleus interaction simulations for neutrino oscillation experiments.

Author Contributions: This analysis was performed within the Neutrino Interactions Working Group of the T2K experiment and was a principal topic of J.M.'s PhD thesis [8]. Conceptualization, all authors.; methodology, all authors; software, J.M., Y.H. and L.P.; validation, all authors; formal analysis, J.M., S.D., G.M., K.N. and L.P.; investigation, all authors; writing—original draft preparation, S.D.; writing—review and editing, S.D.; visualization, J.M.; supervision, S.D., G.M., K.N., L.P. and L.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by: CEA, France; P2IO LabEx (ANR-10-LABX-0038) in the framework 'Investissements d'Avenir' (ANR-11-IDEX-0003-01) managed by the 'Agence Nationale de la Recherche' (ANR), France; H2020 grant number RISE-GA822070-JENNIFER2 2020; the Spanish Ministerio de Ciencia e Innovación and ERDF (European Regional Development Fund) under Contract No. PID2020-114687GB-100, by the Junta de Andalucía (FQM 160); the University of Tokyo ICRR's Inter-University Research Program FY2023 (Ref. 2023i-J-001); U.S. Department of Energy, Office of Science, Office of High Energy Physics, Award DE-SC0008475; JSPS KAKENHI Grant Number

JP18H05536; STFC, UK; Special Research Fund, Ghent University; the Polish National Science Centre (NCN) grant No. 2020/37/N/ST2/01751.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Alvarez-Ruso, L.; Athar, M.S.; Barbaro, M.B.; Cherdack, D.; Christy, M.E.; Coloma, P.; Donnelly, T.W.; Dytman, S.; de Gouvêa, A.; Hill, R.J.; et al. NuSTEC White Paper: Status and challenges of neutrino–nucleus scattering. *Prog. Part. Nucl. Phys.* **2018**, *100*, 1–68. [\[CrossRef\]](#)
2. Abe, K.; Abgrall, N.; Aihara, H.; Ajima, Y.; Albert, J.B.; Allan, D.; Amaudruz, P.-A.; Andreopoulos, C.; Andrieu, B.; Anerella, M.D.; et al. The T2K experiment. *Nucl. Instrum. Meth. A* **2011**, *659*, 106–135. [\[CrossRef\]](#)
3. Fukuda, Y.; Fukuda, Y.; Hayakawa, T.; Ichihara, E.; Ishitsuka, M.; Itow, Y.; Kajita, T.; Kameda, J.; Kaneyuki, K.; Kasuga, S.; et al. The Super-Kamiokande detector. *Nucl. Instrum. Meth. A* **2003**, *501*, 418–462. [\[CrossRef\]](#)
4. Abe, K.; Abe, K.; Aihara, H.; Aimi, A.; Akutsu, R.; Andreopoulos, C.; Anghel, I.; Anthony, L.H.V.; Antonova, M.; Ashida, Y.; et al. Hyper-Kamiokande Design Report. *arXiv* **2018**, arXiv:1805.04163.
5. Hayato, Y.; Pickering, L. The NEUT neutrino interaction simulation program library. *Eur. Phys. J. Spec. Top.* **2021**, *230*, 4469–4481. [\[CrossRef\]](#)
6. Pinzon Guerra, E.S.; Wilkinson, C.; Bhadra, S.; Bolognesi, S.; Calcutt, J.; de Perio, P.; Dolan, S.; Feusels, T.; Fiorentini, G.; Hayato, Y.; et al. Using world charged pion–nucleus scattering data to constrain an intranuclear cascade model. *Phys. Rev. D* **2019**, *99*, 052007. [\[CrossRef\]](#)
7. Fukuda, Y.; Hayakawa, T.; Ichihara, E.; Inoue, K.; Ishihara, K.; Ishino, H.; Itow, Y.; Kajita, T.; Kameda, J.; Kasuga, S.; et al. Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.* **1998**, *81*, 1562–1567. [\[CrossRef\]](#)
8. McElwee, J. Tuning Neutrino Interaction Models to Inclusive Electron Scattering Data. Ph.D. Thesis, University of Sheffield, Sheffield, UK, 2022. Available online: <https://etheses.whiterose.ac.uk/32248/> (accessed on 16 June 2023).
9. Khachatryan, M.; Papadopoulou, A.; Ashkenazi, A.; Hauenstein, F.; Nambrath, A.; Hrnjic, A.; Weinstein, L.B.; Hen, O.; Piasetzky, E.; Betancourt, M.; et al. Electron-beam energy reconstruction for neutrino oscillation measurements. *Nature* **2021**, *599*, 565–570. [\[CrossRef\]](#)
10. Papadopoulou, A.; Ashkenazi, A.; Gardiner, S.; Betancourt, M.; Dytman, S.; Weinstein, L.; Piasetzky, E.; Hauenstein, F.; Khachatryan, M.; Dolan, S.; et al. Inclusive electron scattering and the genie neutrino event generator. *Phys. Rev. D* **2021**, *103*, 113003. [\[CrossRef\]](#)
11. Ankowski, A.M.; Friedland, A. Assessing the accuracy of the GENIE event generator with electron-scattering data. *Phys. Rev. D* **2020**, *102*, 053001. [\[CrossRef\]](#)
12. Gueye, P.; Bernheim, M.; Danel, J.F.; Ducret, J.E.; Lakéhal-Ayat, L.; Goff, J.M.L.; Magnon, A.; Marchand, C.; Morgenstern, J.; Marroncle, J.; et al. Coulomb distortion measurements by comparing electron and positron quasielastic scattering off ¹²C and ²⁰⁸Pb. *Phys. Rev.* **1999**, *60*, 044308. [\[CrossRef\]](#)
13. Bodek, A.; Cai, T. Removal energies and final state interaction in lepton nucleus scattering. *Eur. Phys. J.* **2019**, *79*, 293. [\[CrossRef\]](#)
14. Formaggio, J.A.; Zeller, G.P. From eV to EeV: Neutrino cross sections across energy scales. *Rev. Mod. Phys.* **2012**, *84*, 1307–1341. [\[CrossRef\]](#)
15. Benhar, O.; Fabrocini, A.; Fantoni, S.; Sick, I. Spectral function of finite nuclei and scattering of GeV electrons. *Nucl. Phys.* **1994**, *579*, 493–517. [\[CrossRef\]](#)
16. Rocco, N.; Lovato, A.; Benhar, O. Comparison of the electromagnetic responses of ¹²C obtained from the Green’s function Monte Carlo and spectral function approaches. *Phys. Rev. C* **2016**, *94*, 065501. [\[CrossRef\]](#)
17. Gonzalez-Jimenez, R.; Megias, G.D.; Barbaro, M.B.; Caballero, J.A.; Donnelly, T.W. Extensions of superscaling from relativistic mean field theory: The SuSAv2 model. *Phys. Rev.* **2014**, *C90*, 035501. [\[CrossRef\]](#)
18. Megias, G.D. Charged-Current Neutrino Interactions with Nucleons and Nuclei at Intermediate Energies. Ph.D. Thesis, University of Seville, Seville, Spain, 2017. Available online: <https://idus.us.es/xmlui/handle/11441/74826> (accessed on 16 June 2023).
19. Ankowski, A.M.; Benhar, O.; Sakuda, M. Improving the accuracy of neutrino energy reconstruction in charged-current quasielastic scattering off nuclear targets. *Phys. Rev. D* **2015**, *91*, 033005. [\[CrossRef\]](#)
20. Abe, K.; Akhlaq, N.; Akutsu, R.; Ali, A.; Alt, C.; Andreopoulos, C.; Antonova, M.; Aoki, S.; Arihara, T.; Asada, Y.; et al. Improved constraints on neutrino mixing from the T2K experiment with 3.13×10^{21} protons on target. *Phys. Rev. D* **2021**, *103*, 112008. [\[CrossRef\]](#)
21. Cai, T.; Lu, X.-G.; Harewood, L.A.; Wret, C.; Akbar, F.; Andrade, D.A.; Ascencio, M.V.; Bellantoni, L.; Bercellie, A.; Betancourt, M.; et al. Nucleon binding energy and transverse momentum imbalance in neutrino–nucleus reactions. *Phys. Rev. D* **2020**, *101*, 092001. [\[CrossRef\]](#)
22. Benhar, O.; Day, D.; Sick, I. An archive for quasi-elastic electron–nucleus scattering data. *arXiv* **2006**, arXiv:nucl-ex/0603032.

23. Acero, M.A.; Adamson, P.; Agam, G.; Aliaga, L.; Alion, T.; Allakhverdian, V.; Anfimov, N.; Antoshkin, A.; Asquith, L.; Aurisano, A.; et al. Adjusting neutrino interaction models and evaluating uncertainties using NOvA near detector data. *Eur. Phys. J. C* **2020**, *80*, 1119. [CrossRef]
24. Bronner, C. Neutrino 2022 Plenary Talk Accelerator Neutrino I_Recent Results from T2K. 2022. Available online: <https://zenodo.org/record/6683821>. (accessed on 16 June 2023).
25. Dolan, S. Modelling Neutrino-Nucleus Interactions for the T2K Experiment. Available online: <https://indico.cern.ch/event/881216/contributions/5108384/> (accessed on 28 November 2022).
26. Rodrigues, P.A.; Demgen, J.; Miltenberger, E.; Aliaga, L.; Altinok, O.; Bellantoni, L.; Bercellie, A.; Betancourt, M.; Bodek, A.; Bravar, A.; et al. Identification of Nuclear Effects in Neutrino-Carbon Interactions at Low Three-Momentum Transfer. *Phys. Rev. Lett.* **2016**, *116*, 071802. Erratum in *Phys. Rev. Lett.* **2018**, *121*, 209902. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.